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Red Palm Weevil *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae): Global Invasion, Current Management Options, Challenges and Future Prospects

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Abstract

The red palm weevil (RPW) *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae) also known as the Asian palm weevil is a key pest of palms (Arecaceae) in diverse agro-ecosystems the world over. During March 2017, the Food and Agricultural Organization of the UN through its 'Rome Declaration' called for the urgent need to combat RPW by collaborative efforts and commitments at the country, regional and global levels to stop the spread of this devastating pest. There exist gaps and challenges in almost all the components of the current RPW-IPM strategy, particularly with regard to early detection, developing and implementing phytosanitary measures, lack of effective biological control agents in the field and poor farmer participation in the control programmes, which have made RPW control and eradication extremely difficult. This chapter gives an overview of the global invasion, current management options, challenges and future prospects for its effective control.

Keywords: invasive species, red palm weevil, IPM, introduction pathways, quarantine insect

1. Introduction

The red palm weevil (RPW) *Rhynchophorus ferrugineus* (Coleoptera: Curculionidae) also known as the Asian palm weevil is an invasive key pest of palms (Arecaceae) in diverse agro-ecosystems the world over. The Food and Agriculture Organization of the UN has designated RPW as a category-1 pest in the Middle East and North Africa (NENA region), where it is a threat to the livelihood security of date palm farmers in rural communities [1]. During March 2017, FAO organized a 'Scientific and High-Level Meeting on the Management of RPW' and through 'Rome Declaration' called for the urgent need to combat RPW by collaborative efforts and commitments at the country, regional and global levels to stop the spread of this devastating pest. The pest has its home in South and South East Asia, where it is a key pest of coconut, *Cocos nucifera*. The cryptic behaviour and the intrinsic biological traits of the weevil have made it difficult to detect and therefore difficult to manage. Now, there are so many gaps and challenges in the components of RPW management

strategies. These include early detection of the weevil infestation, limitation of its biological control agents under field conditions and lack of farmers’ participation in the control operations [2]. The aim of this chapter is to give a consolidated information on gaps and challenges in current RPW management as well as future prospects.

2. Global RPW invasion: an update

During the mid-1980s, RPW was reported on date palm *Phoenix dactylifera* L. from the United Arab Emirates in the Gulf region of the Middle East. Subsequently, first reports of RPW invasion came from the other Gulf countries of the Middle East. During 1993, RPW attack was reported on date palm in Egypt in North Africa, and later during 1995, it was detected for the first time on *P. canariensis* from Spain in Europe. During the next two decades, the pest spread rapidly in the Gulf region of the Middle East, some Maghreb countries in North Africa and the Mediterranean basin countries in Europe (Figure 1). RPW has rapidly expanded its geographical range during the last three decades, and ecological niche modeling [3] suggests that the pest is likely to expand its geographical range still further. Recent reports of RPW invasion suggest that the pest is establishing in East Africa in Djibouti on date palm and also in the Caucasian region where it is detected in Abkhazia on the canary island palm in the Republic of Georgia. During 2019, RPW was detected in Bulgaria in the Black Sea Basin region and also in Bosnia-Herzegovina in Southeastern Europe.

The only report of RPW invasion in the American continent comes from Aruba and Curacao islands in the Caribbean region [4]. Although RPW was reported from California, USA, during 2010 [5], molecular studies at the University of California, USA, subsequently characterized the pest as *R. vulneratus* [6], a closely related species of *R. ferrugineus* predominant on coconut in the South East Asia. Similarly, the previous *R. ferrugineus* reports from Australia and countries in the Oceanic region have now been attributed to other species of the *Rhynchophorus* group of weevils. It is pertinent to point out that although RPW moves through infested offshoots in the date palm-growing countries, another important route of transmission/movement of the pest is through palms shipped for ornamental gardening.

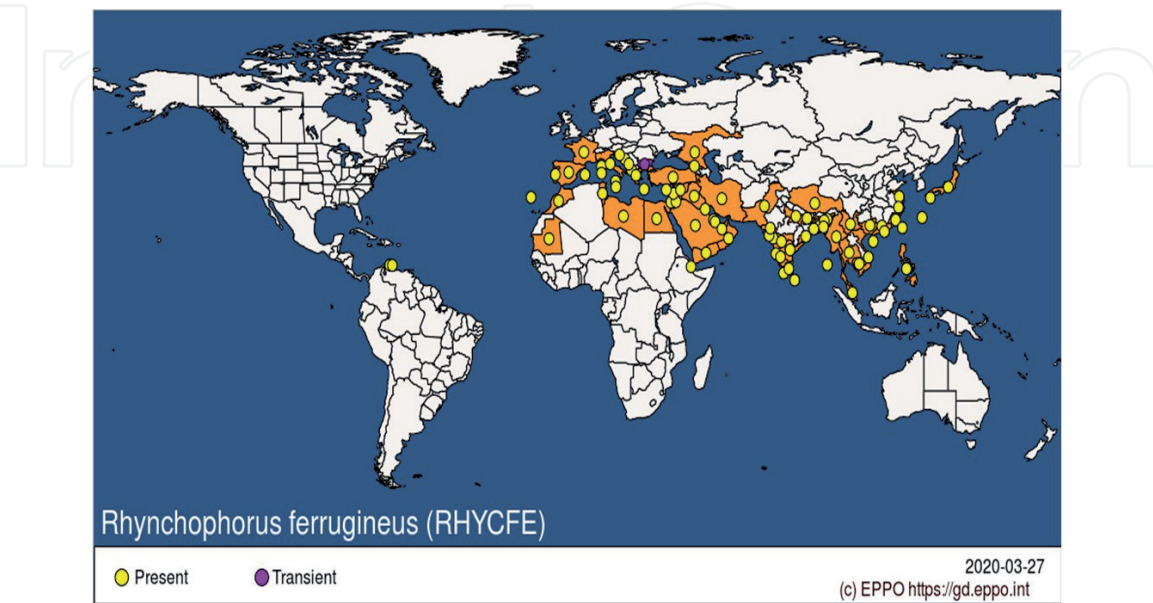


Figure 1. Current Geographical Distribution of RPW (Source- EPPO 2020; <https://gd.eppo.int/taxon/RHYCFE/datasheet>).

The recent *R. ferrugineus* data sheets of the European Plant Protection Organization [7] reports that RPW exists in 49 countries including 15 in Europe (Albania, Bosnia-Herzegovina, Croatia, Cyprus, France, Georgia, Greece, Italy, Malta, Montenegro, Morocco, Portugal, Russia, Spain and Turkey), six in Africa (Djibouti, Egypt, Libya, Mauritania, Morocco and Tunisia), 26 in Asia (Bahrain, Bangladesh, Cambodia, China, India, Iran, Iraq, Israel, Japan, Jordan, Kuwait, Lebanon, Malaysia, Myanmar, Oman, Pakistan, the Philippines, Qatar, Saudi Arabia, Sri Lanka, Syria, Taiwan, Thailand, the United Arab Emirates, Vietnam and Yemen) and two in the American continent (Aruba and the Netherlands Antilles).

3. Host range and introduction pathways

As the geographical range of the pest expanded, so did the host range of RPW. During the mid-1950s, RPW was reported from just four palm species, viz. *C. nucifera*, *P. dactylifera*, *Metroxylon sagu* and *Corypha umbraculifera* [8]. RPW is currently reported on 40 palm species worldwide [7, 9, 10], including *Areca catechu* L., *Arenga saccharifera* Labill, *A. engleri* Becc., *A. pinnata* (Wurmb), *Bismarckia nobilis* Hildebrand and Wend, *Borassus flabellifer* L., *B. sp.*, *Brahea armata* S. Watson, *B. edulis*, *Butia capitata* (Mart.) Becc., *Calamus merrillii* Becc., *Caryota cumingii* Lodd., *C. maxima* Blume, *Cocos nucifera*, *Corypha utan* Lamk., (= *C. gebanga*, *C. elata*), *C. umbraculifera* L., *Chamaerops humilis*, *Elaeis guineensis*, *Livistona australis* (R.Br.) Mart., *L. decipiens* Becc., *L. chinensis* Jacq.R. Br., *L. saribus* (= *L. cochinchinensis*) (Lour.) Merr., *Metroxylon sagu* Rottb., *Oncosperma horrida* (Scheff.), *O. tigillarum* (Ridl.), *Phoenix canariensis* (Chabaud), *P. dactylifera*, *P. roebelinii* O'Brien, *P. sylvestris* Roxb, *P. theophrastii* Greuter, *Pritchardia pacifica* Seemann and Wendland, *P. hillebrandii* (Kuntze) Becc., *Ravenea rivularis* Jumelle and Perrier, *Roystonea regia* (Kunth.), *Sabal umbraculifera* (Jacq.) Martius, *Trachycarpus fortunei* (Hook), *Washingtonia filifera* (L. Lindl), *W. robusta* H. Wendl. and *Syagrus romanzoffiana* (Cham.). The non-palm hosts are the century plant *Agave americana* and sugarcane *Saccharum officinarum* [9].

Considering such a wide host range of this pest, it is imperative to ensure proper phytosanitary measures are in place before palms are transported/shipped. Recently, FAO has published the detailed guidelines on phytosanitary regulations to be adopted to ensure the movement of RPW free planting material within national borders and from one country to another [11]. Import and movement of infested plant material within a country are the main pathways to the introduction and spread of *R. ferrugineus*. Short-distance spread is possible by adult flight. The pest can be spread over long distances in infested palms for planting of host palms [7]. Flight mill studies have demonstrated that RPW being a sizeable population is short-distance fliers (<100 m) which would explain the aggregated/clumped distribution of infestation. RPW has the capacity to fly up to 50 km in a day with flight activity being predominantly diurnal [12–14].

4. Biology and symptoms of damage

Understanding the biology of the pest is essential in developing, implementing and sustaining management practices. RPW is a hidden pest, with all its life stages developing inside the palm except for the adult stage, which is partly exposed when adult weevils fly out of the brood in search of the host or on occasions to find a mate.

Recently, Al-Ayedh [15] in the FAO guidelines on RPW management and EPPO [7], using RPW data sheets, has summarized the literature on the biology of this pest.

There are several previous reports on the biology of RPW on natural and artificial diets [8, 16–23]. **Figure 2** depicts the life stages with the probable duration of each stage.

RPW takes about 3–4 months to complete its life cycle. Volatiles released from fresh wounds/cuts on the palm helps in egg laying by attracting adult RPW female weevils. Gravid females lay eggs in cracks and crevices on soft palm tissue. In coconut and date palm, oviposition usually occurs in young palms below 20 years old. There is a weak relationship between *Oryctes* sp. infestations and RPW attack in coconut and date palm [24, 25]. An adult female lays over 200 eggs. Oviposition is strongly affected by temperature [22]. On hatching, the legless larvae start feeding and move towards the interior of the palm. In areas with a mean annual temperature (MAT) below 15°C, one generation per year can be expected, while more than two generations in those with MAT above 19°C. Several overlapping generations of the pest may occur inside a single infested palm. Further, in the Mediterranean region, the larval stage can get prolonged up to 160 days in winter-spring seasons [22]. Upon completion of the larval period (7–16 instars), mature larvae pupate in cylindrical fibrous cocoons, leading to the emergence of adult weevils (**Figure 2**). When RPW was reared in the laboratory on a meridic diet, some of the larvae successfully pupate and develop to adults without construction of cocoons (**Figure 3**) (El-Shafie, unpublished data).

Date palms below the age of 20 are more susceptible to attach by RPW. Infestation is found more common on the trunk within 1 m from the ground; however, infestation can occurs on aerial offshoots and the crown of male palms [26]. Damage symptoms on Date palm (*Phoenix dactylifera*) have been described in detail [26–28]. The main symptoms include the following:

- i. Oozing of brownish viscous fluid together with frass (palm tissue excreted by feeding grubs) which has a typical fermented odour
- ii. Drying of outer leaves and fruit bunches and drying of infested offshoots

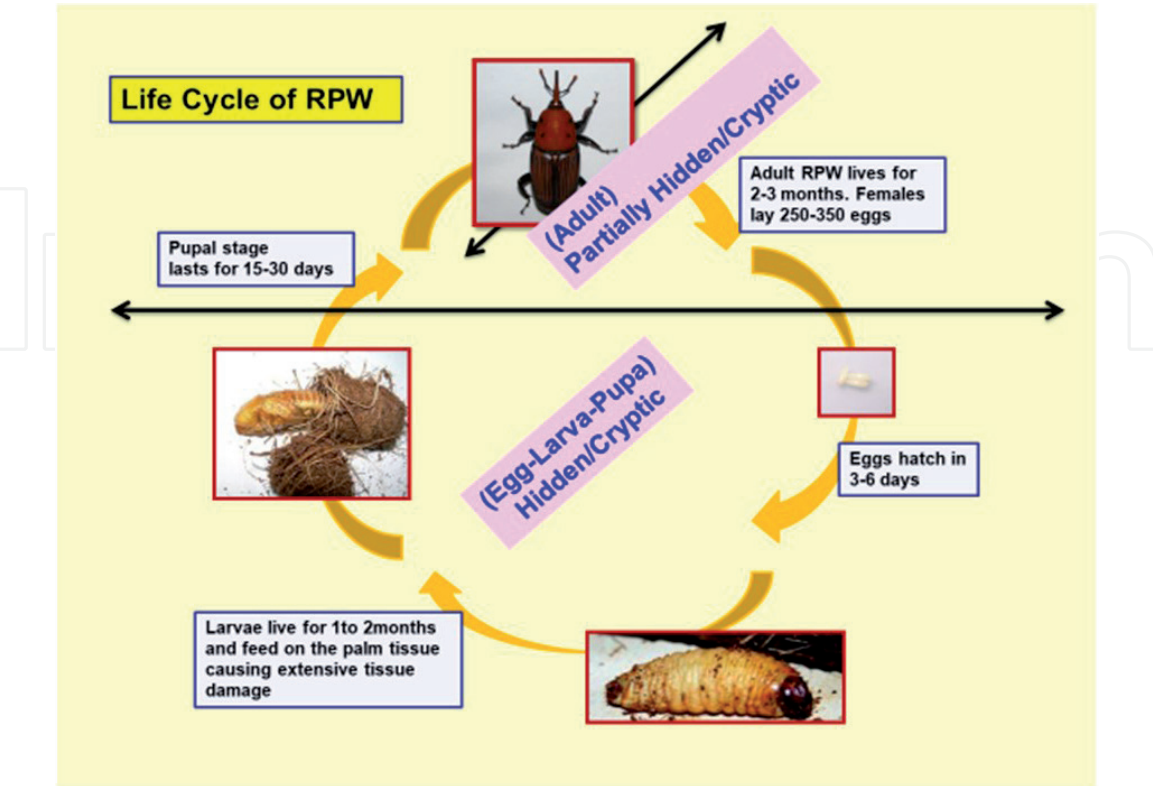


Figure 2. Schematic Diagram Depicting the Life Cycle of RPW (Source: Faleiro and Al-Shawaf 2018; <http://hdl.handle.net/20.500.11766/8914>).

- iii. Topping of the trunk in case of severe and extensive tissue damage
- iv. Presence of adults and pupae at the base of the fronds and on the ground near infested palms



Figure 3.
Successful emergence of a viable RPW adult from a pupa without fibrous cocoon (Photo: Hamadttu A. F. El-Shafie).



Figure 4.
Drying or withering of aerial offshoots, the fronds of which can be easily pulled out (left). Oozing out of brown viscous unpleasant liquid from wounds in the trunk (right) (Photo: Hamadttu A. F. El-Shafie).



Figure 5. Ejection of chewed-up fibers from the crown of an infested young date palm (left). Smashed internal palm tissue due to feeding of grubs (Photo: Hamadttu A. F. El-Shafie).

Visual symptoms of damage on palms are used for early detection of RPW infestation. Thus, it is of paramount importance for field inspectors and palm growers to understand these symptoms (**Figures 4 and 5**). On Canary Island palm (*Phoenix canariensis*), infestation and damage occur in the crown. The larvae tunnel in the developing leaves (fronds) and severe infestation may lead to palm mortality. Early symptoms include the presence of holes in the fronds, which look chewed and broken. Wilting and drying of developed fronds and absence of new emerging fronds cause asymmetrical growth of the crown that later collapse. As is the case with date palm, different stages of the weevil can be seen at the crown particularly when infestation is more severe [29].

5. Current RPW management programmes

In areas where the pest does not exist but under the potential risk of infestation occurring, it is essential to emphasize on quarantine, monitoring/surveillance and capacity building.

A new infestation report calls for immediate removal and destruction (eradication) of the RPW infested palm right at the sight/farm where the infestation is detected. Subsequently, a surveillance programme based on a regular inspection to detect infestation and monitor trapping to capture emerging adults needs in the demarcated area to ensure effective control, containment and eradication of the pest. Chouibani [11] in the FAO guidelines proposed to identify the infested zone where the presence of RPW is confirmed and also a buffer zone extending at least 10 km beyond the boundary of the infested zone. A strict vigil is to be maintained on the movement of palms and plant nurseries within the demarcated area. The demarcated area will be declared free from RPW if, during three consecutive years, RPW has not been detected [11].

Geographic information system (GIS) provides a very valuable tool in monitoring, predicting, managing and fighting the spread of pests and diseases, and

GIS-based techniques are increasingly used to enhance and support decision-making capabilities in RPW management [30–33]. This tool offers opportunities for cost-effective and efficient targeting of control interventions. In monitoring, GIS can be used to determine the spatial extent of a pest, to predict the projected spread, to provide input for risk assessment models. The first and essential step for efficient use of GIS techniques at a larger scale is a protocol for data collection. This will help to have a grip of the situation and is essential to periodically validate the RPW control programme, where data on infestation reports and trap captures are important. Fajardo et al. [33] proposed the following with regard to the use of GIS in area-wide RPW management programmes:

- Maintain a field map of each operational area indicating the basic data (number of palms, year of planting, number of traps, number of infested palms, palms removed, palms treated, etc.).
- Register the GPS co-ordinates of all the palms in a geographical data base if possible. The more important fields to be included are: date, area, height and state (not infested, infested and palms removed with GPS co-ordinates). It is also recommended to register the coordinates of the already removed palm trees.
- Data on the geo-reference localization of the palms, the RPW-IPM components and their evolution over time using GIS to elaborate maps and analysis need to be developed.
- FAO has proposed a real-time database and a web portal for the management of RPW at the local, national and Near East and North Africa (NENA) region. Furthermore, a mobile app for android and iOS smartphones to record geo-referenced data at the field location on a standard form needs to be developed. FAO has made initiatives in this regard both at the regional (NENA) and global levels [34, 35].

In any area-wide IPM programmes, the means (resources) to control the pest can be correlated with the intensity of the pest. Ferry et al. [36] visualized three scenarios to exist in the current RPW-IPM strategy depending on the resources available to control the RPW, considering that the organization and techniques are optimum and similar for the three scenarios:

1. The means are superior to the needs: here the resources are adequate and the pest is controlled/eradicated.
2. The means remain more or less equal to the needs: here there is a prolonged effort to control the pest over several years with little or no success and the pest is always ahead with the IPM strategy trying to catch up. Such a scenario is not sustainable in the long run.
3. The means are inferior to the needs: here the pest is not controlled and proliferates rapidly. The control means are inadequate.

It has been seen in several countries that providing adequate man power and material is a major challenge in all area-wide RPW control programmes. It is essential to provide adequate resources right at the beginning of the first record of this pest so that RPW can be efficiently controlled and eradicated when the pest is confined to a few farms/small area.

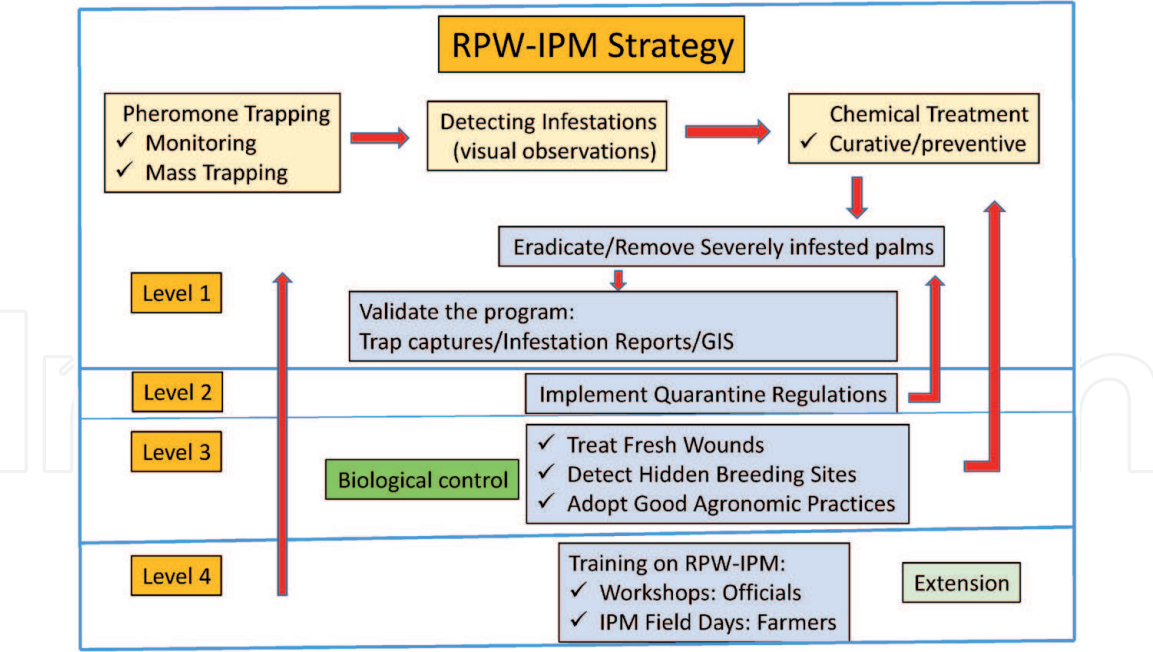


Figure 6.
RPW-IPM strategy implemented (Updated from <http://www.fao.org/3/a-ms665e.pdf>).

Figure 6 depicts the components of the current RPW-IPM strategy at four levels. At level-1, the strategy realizes the control components at the operational level on a daily basis in the field. The area-wide management of RPW needs careful planning and timely intervention of the control techniques, able supervision and periodic performance analysis of the RPW-IPM strategy, besides the desired technical, human, intuitional, organizational and coordination capacities for effective planning, delivery, monitoring and management of RPW in the field.

At level-1 of the strategy, the RPW-IPM components connected with the day-to-day operations in the field are highlighted [37].

5.1 Detection of infested palms

Success of an RPW-IPM programme lies in the early detection of infested palms, and currently, visual inspection of palms is widely adopted to locate infested palms. Here, it is essential to break the cycle of the pest by locating an infested palm before adults emerge. A well-trained person can inspect 200–300 date palms per day depending on the terrain, palm density and field sanitation techniques adopted. In this context, a regular 45-day interval inspection of date palms in the susceptible age group of less than 20 years old is necessary. Vidyasagar [38] and Jaques [29] have detailed the protocols for visual inspection of the date and Canary island palms, respectively, in the FAO guidelines for RPW management. Research is underway in several countries to develop a cost-effective and user-friendly early detection device. Advanced techniques such as detecting chemical signatures, acoustic detection, use of infrared cameras, thermal imaging and satellite imaging/IoT are being researched upon [39–43]. However, farmers have to rely on visual (manual) inspection to detect an RPW infested palm, as these techniques are limited by their cost and the need for installing sophisticated hardware that is not easy to operate and requires specialized staff to operate.

5.2 Pheromone trapping

Ever since Hallett et al., [44] discovered the male-produced aggregation pheromone (ferrugineol) for RPW, food-baited (natural kairomone) bucket traps have

been widely used in monitoring and mass trapping programmes in the field. Over the years, trapping protocols with respect to trap design, trap colour, lures, release rate, food bait, trap servicing (periodic change of food bait), role of co-attractants, etc. have been researched in several countries [29, 45–50]. Pheromone trap captures help optimizing/prioritizing the inspection of palms to detect infestations. Depending on the availability of human resources, palms around the traps with higher weevil captures should be inspected on priority. El-Shafie and Faleiro [51] reported through the controlled olfactometer studies that only a part of the adult population is attracted to the pheromone lure, which calls for the integration of pheromone trapping with other RPW-IPM techniques. There is a tendency of over-dependency on pheromone trapping and neglecting other RPW-IPM components, which leads to the build up and proliferation of the pest. Although the four-window black coloured bucket traps are popular, the dome-shaped conical Picusan™ is also used in several European countries.

It is of utmost importance to adopt the best trapping protocols with respect to trap design, trap colour, density, servicing (periodic renewal of food bait), trap placement, lure attraction and longevity, etc., for food-baited RPW pheromone traps. Sub-standard trapping protocols would adversely impact the trapping efficiency and consequently limit the success of the control programme [52, 53]. In some countries, the food bait and water are placed in a small container inside the bucket trap. Often this container is insufficient to hold the required amount of the bait or falls inside the bucket, emptying the water resulting in the food becoming dry, which consequently adversely impacts the performance of the trap due to poor bait-lure synergy. It is therefore recommended to place the required amount of the food bait (150–200 g of dates) directly in the water (1 L) inside the bucket trap. Of utmost importance is the fortnightly servicing (replacement of the food bait and water) in the trap. An economic rationale would demand that easily available locally sourced food baits with good attraction to be used as bait in the trap. Consequently, green coconut petiole pieces would do well in the coconut growing countries of South and South East Asia, low-grade dates in the Middle East and North Africa and palm tissue/petiole pieces in the Mediterranean region where the Canary Island palm is popular. Pheromone lures are known to last for 2–3 months in the field. Adding a small amount (1 g) of non-repellent insecticide granules (carbofuran/lanate) to the water in the trap could be useful in preventing the escape of adult weevils that enter the trap. However, in several countries where thousands of traps are in the field, the addition of insecticide in the trap is not practiced in view of the toxic side effects to the environment and potential harm to the staff who service the traps. Pheromone lures with both high attraction and field longevity should be selected. Do not discard old lures in the field or carry old lures to the residences of staff working in the field. These are to be brought back to the operations unit and incinerated or buried deep in the ground. Co-attractants (synthetic kairomones) such as ethyl acetate/ethyl alcohol are known to enhance captures in RPW pheromone traps, but could also significantly increase the cost of an area-wide control programme [54–57].

As regards trap density, in surveillance programmes, set traps along the motorable roads @1 trap for every km. Depending on the pest intensity in mass trapping programmes, 1–4 traps/ha can be adopted [58]. Usually 1 trap/ha is deployed and if more traps are to be set in the field, use service-less trapping options (Attract and Kill; Dry trap-Electrap™) when trap density has to be enhanced beyond 1 trap/ha. Set traps preferably on the ground under the shade with around half of the bucket trap inserted into the soil. Do not place traps directly on young palms. Numbering/geo-referencing of every trap in the field is indispensable for periodic review of the situation in the field and mobilizing resources around traps with high

weevil captures. It is important to emphasize that poor bait lure synergy due to sub-standard trapping protocols would end up in the palm smelling better than the trap and attracted weevils getting oriented to the palm instead of entering the trap. This is a very dangerous situation where a poorly maintained trap acts as a catalyst in creating new infestations.

Although the food-baited RPW pheromone trap is most popular, the periodic replacement of the food bait is cumbersome and not sustainable in the long run, especially in area-wide control programmes. In this context, bait and trap free technique of attract and kill has been tested and used to curtail the emerging adult RPW population [59, 60]. Another service-less RPW trapping option that works without the food bait/water is the dry Electrap™ [48]. The cost of incorporating these techniques in an area-wide control programme could be a factor to be considered and needs to be compared with the traditional food-baited pheromone trap before adoption. Large-scale control programmes would stand to benefit if smart traps capable of recording and transmitting weevil capture data on a 24×7 basis are developed. In this context, Potamitis et al. [61] and Aldhryhim and Al-Ayedh [62] have developed and tested smart traps for RPW, but these need advancement for large-scale deployment in the field. An ideal RPW pheromone trap would be the one that does not need servicing and automatically transmits weevil capture data on a 24×7 basis to the operations control unit.

5.3 Chemical treatments

Preventive and curative chemical treatments are essential for the efficient management of RPW [27, 63]. Fajardo [64] and Aldawood [65] have described protocols for these treatments in detail.

5.3.1 Preventive treatments

Preventive chemical treatments are often abused and deployed unnecessarily on a calendar basis resulting in drawbacks associated with these treatments, such as pest developing resistance to chemical pesticides, residues of the chemicals in the fruit (dates/coconut) and resurgence of secondary pests and contamination of the environment. Recent reports suggest that RPW is developing resistance to the several insecticides [66, 67]. Overdependence on pesticide application in date plantations has resulted in the residue level of certain insecticides and acaricides being higher than the maximum residue levels permitted in dates [68]. Preventive treatments should only be carried out in farms with high weevil activity as gauged from high infestation and the removal of infested palms/high trap captures/high seasonal activity in the Middle East during March–May and September–October. It is imperative to treat all fresh wounds on palm immediately after the frond and offshoot removal [26, 69–71]. These operations of cleaning the palm could be preferably adopted during the peak winter months when temperatures are low and not conducive for egg hatch and larval development. The commonly used insecticides for preventive treatments are imidacloprid, thiamethoxam, avermectin, abamectin, chlorpyrifos and phosmet. It should be borne in mind that the preventive insecticide treatments are often unnecessary and excessive, which would have negative impact on the environment as a whole.

5.3.2 Curative treatments

The curative insecticidal treatment of RPW-infested palms in the early stage of attack is an integral part of the control strategy. Such palms recover with insecticide

treatment [63, 72, 73]. Ferry [74] provided a detailed protocol of mechanically sanitizing palms in the early stage of attack, while Aldawood [65] presented a comprehensive protocol to inject palms with insecticide in the early stage of attack. Although pressure injectors are used to deliver the insecticide solution to the infested site inside the palm, this technique could damage the palm tissue if the pressure exceeds 2 bar. The diffusion method (gallon method) by cleaning the palm around the infested site on the palm, drilling 4–6 slanting holes 20 cm deep at an angle and pouring insecticide solution into each of the holes is simple, cost-effective and safe. Treat the palm again after 15 days. Once the palm recovers and if the infestation site is close to the ground, cover the treated site with soil to facilitate rooting. For ornamental palms, including ornamental date palms, a new injection technique based on the microinfusion of avermectin insecticide allows to protect the palms at a very low cost over a period of 1 year [75]. Commonly used insecticides for curative treatments are the following: imidacloprid, thiamethoxam, avermectin and abamectin. In organic date plantations, the proven plant origin insecticides would have to be used to treat RPW-infested palms. Several pressure injectors are available in the market which should be used with extreme caution (not >2 bar pressure), to avoid rupture of palm tissue that can lead to death of the treated palm. Ferry and Gomez [63] recommend that only a limited number of stem injections may be carried out in ornamental palms while prohibiting stem injection on a preventive basis in palms grown as food crops.

5.4 Removal of severely infested palms

Even in well-managed RPW-IPM programmes, a certain percentage of the infestations detected is in the advanced stage of attack, where such palms exhibit large tissue damage often harbouring adult weevils with overlapping generations of the pest and have to be removed (eradicated). Such palms disperse adult weevils in the field that result in new infestations which reverse the achievements made in controlling the pest. It is of utmost importance to detect infestations before adult weevils emerge and disperse. Al-Shawaf et al. [76] validated an area-wide RPW IPM programme in the Al-Ahsa oasis of Saudi Arabia using palm removal (eradication) data as a criterion to judge the success of the field operations. Palm eradication levels above 20% of the infested palms are not desirable, which reveals that the pest is proliferating and control tactics need adjustments.

Vidyasagar [77] outlined a detailed protocol for the safe removal and disposal of severely infested palms. The protocol broadly recommends to the following:

1. Identify the badly infested or damaged palms and mark all such palms with a distinct colour tape or spray paint, or a specific number of straps. Infestation due to RPW could be considered severe in date palms if more than 30% of the trunk tissue is damaged at the infestation site.
2. Initiate the removal process as soon as possible. Otherwise, the adults from these infested palms will make their way to healthy palms in the vicinity, making the task much more difficult.
3. As a prophylactic measure, soak, drench or shower the palm crown and also the trunk and bole regions with a recommended pesticide.

In many countries, shredding machines are used to destroy the severely infested palms at another site, where the severely infested palms are cut into logs and the palm pieces (fronds and trunk) are transported to the shredding site.

Utmost care needs to be taken that there are no escapes of the adult weevils during transportation, for which the palm pieces are to be wrapped in plastic wrapping that is sealed with a tape or transported using enclosed trucks. This is a very expensive process and therefore in-situ (on farm site) removal and disposal of severely infested palm tissue by cutting into small pieces (20 × 10 cm) and soaking with insecticide is recommended [75]. In some countries, the removal of severely infested palms is outsourced to private agencies. Here, bureaucratic procedures in issuing work orders to contractors often result in delay which in turn leads to the spread of the weevil.

Abandoned and neglected plantations also harbour the pest and have to be closely monitored for incidence of RPW by intensive inspection campaigns and installing monitor traps. Farmer cooperation to assist in tackling the pest in neglected gardens should also be sought through persistent awareness programmes. The technique of attract and kill is suited for such plantations. If the plantation is dry with no irrigation and the palm tissue is hard, in all probability, RPW will not prefer such a garden. If there is no pest in an abandoned plantation, these palms should not be removed as palm volatiles emitted during the removal process may attract the pest.

5.5 Validating the control programme

In an area-wide RPW IPM programme, the judicious use of resources (men and material) is vital. Often scarce labour and resources have to be used where most required and the control strategy has to be adjusted by providing resources where most needed. In this context, data on weevil captures in traps, infestation reports and removal of severely infested palms could be used to gauge the situation. Faleiro [26] proposed an assumed action threshold of 1% infestation in large plantations. He developed sequential sampling plans to accurately assess the pest status in coconut and date palm [78, 79] based on infestation reports where in the action threshold, the aggregation index of RPW and the risk of making the wrong decision are built into the plan. The sampling plans are efficient tools in decision-making, particularly at very low and high levels of infestation and can be used to assess the performance of RPW- IPM programmes that are in progress. Al-Shawaf et al. [76] analysed the monthly trap capture data, the infestation reports on the removal of severely infested palms and the above sampling plan [79] to categorize infestation in 15 operational areas (4000 ha) in the Al-Ahsa date palm oasis of Saudi Arabia for a period of 6 months between March and September 2011. They found that the IPM strategy adopted had the desired impact in the East of the oasis, but needed minor adjustments in the centre and called for major reinforcement in the North of the Al-Ahsa oasis. Similarly, Hoddle et al. [80] assessed the impact of pheromone trapping, pesticide applications and eradication of the infested date palms for a period of 5 years between 2007 and 2012, for RPW management in 1104 ha in Al Ghowaybah, of the Al-Ahsa oasis in Saudi Arabia. They concluded that the enhanced RPW management programme that commenced in 2009 had a significant impact against the pest.

GIS-based models can also be developed to validate the strategy at periodic intervals based on trap captures and infestation reports [32, 33]. This helps to judiciously use the resources where most required. FAO has proposed a real-time database and a web portal for the management of RPW at the local, national and NENA region. Furthermore, a mobile app for android and iOS smart phones to record geo-referenced data at the field location on a standard form needs to be developed. FAO has initiated the process to validate the *SusaHamra* app to assist farmers in better monitoring and managing the RPW. A global platform is being

established for mapping field data and analytics for better decision-making. Furthermore, remote sensing is being combined with artificial intelligence to map palm trees for the improved monitoring of RPW spread at both the regional and global levels ([34, 35]; <http://www.fao.org/news/story/en/item/1184673/icode/>).

At level-2, the RPW-IPM strategy is to be supported by a robust plant quarantine/phytosanitation regime.

5.6 Quarantine/phytosanitation

Over two decades ago, Abraham et al., [27] first highlighted the importance of quarantine treatments to check the spread of RPW through the infested date palm offshoots and recommended to dip the bole of offshoots before transportation in 0.1% chlorpyrifos for 10 min. In Egypt, quarantine and certification programmes recommend zero tolerance for RPW to block the spread of the pest to secondary foci within planted acreage [81]. Later Faleiro [27] proposed to stop movement of planting material from infested plantations within the country and from one country to another. Wherever this was not possible, it was proposed to implement strict pre- and post-entry quarantine regimes, wherein only pest-free and certified planting material can be transported. Besides date palm offshoots transported for farming, the movement of large palms intended for ornamental gardening contributes largely to the spread of this deadly pest [28]. Hence, it is of utmost importance to keep a strict watch on the movement of planting material (offshoots/palms) for both farming and landscape gardening so that only a treated and pest-free material is allowed to be transported within national boundaries [26, 37]. Al-Shawaf et al. [82] recommended to dip date palm offshoots in 0.004% Fipronil for 30 min before transporting to ensure the complete mortality of the hidden larval stages, if any, and complete certification and transport of the treated offshoots to the new planting site within 72 h of treatment. Studies carried out in Spain in *P. canariensis* suggest that a dose of 1.14 g aluminum phosphide/m³ for 3 days is enough to kill all the stages of RPW in an infested palm tree, and is recommended as a quarantine protocol provided the dose is not phytotoxic to the treated palms [83]. A sound protocol for the treatment of large palms for ornamental gardening needs to be developed.

Although regulations/decrees to regulate the movement of palms for planting exist in several countries, implementing the decrees in letter and spirit is often lacking [37, 84]. In this context, some European Union (EU) guidelines that could be useful are the following: delimitation of survey and demarcated areas, three monthly official inspections of palm nurseries, annual crop declaration, application of phytosanitary treatments, registration of planting material movement and use of plant passport to monitor the trade of palms. Developing certified palm propagation programmes (certified seed) through tissue culture would go a long way ensuring the propagation of a pest-free material. Recently, Chouibani [11] in the FAO guidelines on RPW management outlined detailed phytosanitary protocols for the movement of palms in context of stopping the spread of RPW within national and international borders and proposed to identify the infested zone where the presence of RPW is confirmed and also a buffer zone extending at least 10 km beyond the boundary of the infested zone. A strict vigil is to be maintained on the movement of palms and plant nurseries within the demarcated area. The demarcated area will be declared free from RPW if, during the three consecutive years, RPW has not been detected. Chouibani [11] further recommends that ornamental palm trees originating from recognized nurseries should be imported. Nurseries should be authorized, certified, mapped and regularly inspected by the NPPO of the exporting country.

As regards date palm, only those propagated in vitro in test tubes by laboratories that are officially certified to propagate such materials should be imported.

The RPW-IPM strategy at *level-3* outlines the prospect of palm tolerance to RPW and encourages the use of biological control to combat the pest, besides emphasizing the importance of adopting good agronomic practices.

5.7 Palm resistance to RPW

In perineal crops, such as palms, farmers prefer to cultivate commercial cultivars that are well established and popular in the area/region. These cultivars/varieties are often the most susceptible to RPW. Host plant resistance has not been fully studied and exploited with regard to RPW in spite of some preliminary research that has characterized palm cultivars in terms of tolerance/susceptibility to RPW [20, 85, 86]. The screening techniques to identify resistant RPW cultivars and parental material for use in breeding programmes need to be developed. The molecular markers-assisted breeding programme for the development of RPW resistant cultivars is another avenue that could be pursued. Advanced molecular techniques such as RNAi could hasten the utilization of host plant resistance against RPW [70].

5.8 Agro-techniques and RPW management

Palm density, irrigation methods and protection of tissue immediately after the frond and offshoot removal are probably the most important agro-techniques related to RPW management [87–89].

5.8.1 Palm density

Traditional date palm plantations have palms planted at a close spacing, often restricting sunlight penetration resulting in the build up of in-groove humidity conducive for the development of RPW [90]. Dense planting coupled with flood irrigation and inadequate drainage accelerates the build up of in-groove humidity. In this context, it is recommended to plant new plantations at the recommended spacing to allow sunlight penetration.

5.8.2 Impact of irrigation

In flood-irrigated palms, often, the water touches the trunk at the ground, which encourages adult weevils to oviposit in the collar region of such palms, resulting in new infestations. It is therefore recommended that drip irrigation systems be installed as a precaution for RPW control [87]. Care should be taken to see that palms receive adequate irrigation water as the scarcity of water may result in the incidence of the date palm stem borer *Jebusaea hamerschmidtii* [91].

5.8.3 Protecting fresh wounds

Adult weevils are attracted to palm volatiles emitted from the fresh wounds of palm tissue after the frond and offshoot removal. This calls for the immediate treatment of wounds on the palm to mask the emitting palm volatiles and avoid the gravid female weevil getting attracted to these sites for oviposition. As a precaution, these pruning activities could be carried out during winter when temperatures are low which adversely impacts the egg hatch and larval development [22]. No oviposition was observed for females kept below 15°C [92].

5.9 Biological control

Biological control is an integral part of several sustainable IPM programmes the world over. Biocontrol could play a significant role in augmenting the existing pheromone-based RPW-IPM strategy. Conventional control measures against RPW such as mass pheromone trapping and chemical treatments for preventive and curative purposes have not given the desired level of control. A wide range of RPW natural enemies, viz. insects, bacteria, fungi, viruses, yeasts, entomopathogenic nematodes (EPN) and birds have been reported from several countries [26, 93]. Mazza et al. [94] enlisted more than 50 biological control agents against the *Rhynchophorus* group of weevils. Al-Deeb et al. [95] reported the presence of phoretic mites of the genera *Uropoda*, *Urobovella* and *Curculanoetus* on RPW in UAE. Whether these mites cause a pathological effect on the weevil need to be investigated. In this respect, it has been found that an unidentified species of phoretic mite could cause high mortality among RPW pupae, as well as attenuation of adult weevils (El-Shafie, unpublished data) (**Figure 7**). Yasin et al. [96] reviewed the potential role of potential microbial agents in the control of RPW and concluded that strains of the fungi *Beauveria bassiana* and *Metarhizium anisopliae*, isolated from naturally infected RPW, could contribute to biological control of this pest. There are several publications to show the efficacy of entomopathogenic nematodes (EPN) and the entomopathogenic fungi (EPF) in the laboratory and semi-field assays [96–101].

Laboratory and semi-field cage studies showed the possibility of infecting RPW adults with *B. bassiana* using pheromone traps [100]. Reports from Spain suggest that the EPN, *Steinernema* sp. [99], and the EPF, *B. bassiana* [102], are promising in the field. The role of parasitic tachinid flies from South America against the *Rhynchophorus* group of weevils could also be another potential avenue to explore [103, 104]. The current RPW-IPM programme could be significantly strengthened if the known biological control agents could be delivered to the target site and also sustained in the field.

At level-4, the strategy mainly visualizes capacity building, robust extension programmes to sensitize all stakeholders and farmer participation in the control programme.



Figure 7.
Unidentified phoretic mite on RPW adult (left) and pupa (right) (Photo: Hamadttu A. F. El-Shafie).

5.10 Capacity building and extension programmes

Building the capacity of farmers, home owners and officials is an essential component of the RPW control programme [37]. Dissemination of the latest information on RPW-IPM among all the stakeholders through the electronic and print media can go a long way in strengthening the area-wide RPW-IPM strategy.

5.11 Farmer participation in RPW control

In several countries, an extensive state support is provided while implementing the RPW-IPM programme, keeping the farmers' involvement either bare minimum or almost nil [37]. This makes it very difficult for the authorities to implement the programme. Closed farms, for example, often develop as breeding sites for RPW, diluting the success achieved in controlling the pest in the vicinity of such plantations/home grooves [27]. Farmers' participation and cooperation are vital for any IPM programmes to succeed [105]. Abdedaïem et al. [106] emphasized the need to take up socio-economic studies for better understanding and improving the farmers' involvement in the RPW control programme.

The spread of the pest in vast stretches of date plantations has resulted in outsourcing area-wide RPW-IPM programmes to private companies in some countries. This needs careful planning, implementation and supervision. Here, the lack of experienced staff to oversee operations in the field is a major constraint. Government authorities need to efficiently supervise, monitor and evaluate the control programme implemented by the private company, on a regular basis. Delay in providing necessary inputs (pheromones, insecticides, etc.) where the RPW control is entrusted to private agencies is another major concern. Often there is a delay in finalizing the tender/quotation for the subsequent period before the expiry of the on-going tender resulting in the stoppage of field operations. Any break in the control operations will result in the proliferation and spread of the pest.

6. Challenges of RPW management and future prospects

As a prelude to the scientific consultation and high level meeting on RPW management held in Rome during March 2017, FAO prepared a base document ([1]; <http://www.fao.org/3/a-ms664e.pdf>) on the current situation of RPW in the NENA region where in the present management practices, challenges/weaknesses and available research and technologies for its improvement are outlined. There are several gaps and challenges in the core components of the current RPW-IPM strategy. The current RPW-IPM programmes based on pheromone trapping and other techniques have been implemented with limited success. Gaps and challenges in almost all the components of the strategy, particularly with regard to early detection of the pest, developing and implementing phytosanitary measures, limited efficacy of biological control agents in the field, lack of farmer participation in the programmes and scarcity of data on socio-economic issues among several other factors have made RPW control and eradication extremely difficult. On the positive side, the pest has been eradicated in the Canary Islands and is approaching eradication in Mauritania. Eradication has also been obtained in various oases, but new introductions of infested palms have reversed the success achieved [2].

At level-1 of the strategy, the main challenge in early detection is to provide the farmer with a low cost and efficient detection device. There are several laboratories all over the world that have worked on advanced techniques such as detecting chemical signatures, acoustic detection, use of infrared cameras, thermal imaging,

satellite imaging/IoT, etc. [39–43]. Meanwhile, the visual inspection of palms to detect infested palms will continue to stay to detect RPW infested palms.

With regard to pheromone trapping, the need to regularly service the food-baited traps to change the food bait, water and record weevil captures is cumbersome and is the main constraint. Trap and bait-free trapping (attract and kill) and dry trapping (Electrap™) have addressed the challenge to some extent although data collection on weevil captures continues to be a gap that needs to be addressed. Ideally a dry trap that automatically records and transmits weevil capture data is a prospect for the future. Besides attract and kill, other semiochemical mediated control methods against RPW such as ‘push-pull’, involving the use of repellents and attractants [107], and ‘attract and infect’, involving the spread of biological control agents (EPFs) using pheromone traps [100], needs to be refined and worked upon.

As regards chemical treatments, there is an overdependence on the use of chemical insecticides for both preventive and curative treatments. Research on the efficacy of natural insecticides against RPW needs to be enhanced so that these can be encouraged and incorporated in the control strategy. It is observed that in well-managed plantations, the preventive insecticidal treatments on a regular calendar basis are not required. Furthermore, for curative treatments are pressure injectors really required? These are expensive and need to be operated under the supervision of trained personnel due to the possibility of rupturing the palm tissue leading to death of the palm if the pressure exceeds 2 bar. Instead the methodology for mechanical sanitization coupled with ‘drill and inject’ using the simple diffusion technique has to be standardized.

The removal and safe disposal of severely infested palms is also another huge challenge. In several countries, this aspect of the strategy is constrained by the use of costly shredding machines that need trained personnel to operate. Besides, there is a danger of the weevils escaping during transportation of the eradicated palm to the shredder outside the farm to the shredding site. In this context, Ferry [74] recommends the processing/destruction of severely infested palms right at the farm itself. The possibility of using small portable shredders needs to be looked into.

Area-wide RPW-IPM programmes generate a huge amount of data that needs to be collected, processed and analysed. Periodic validation/performance analysis of the control programme is vital to have a grip of the situation and use the resources judiciously and is an important challenge that has to be met. Any meaningful validation of the control programme calls for meticulous record keeping, particularly of the weevil captures in the traps and the number and location of palms infested, palms treated and removed (eradicated). Record keeping is to be facilitated by having field maps of the operational areas wherein the position of the traps and infested palms can be plotted. Numbering of each trap in the field is vital in addition to geo-referencing all the traps and infestations reported. In the absence of professional GIS specialists in the programme, spatial and temporal spread sheets can be prepared periodically by plotting on the maps (use different colours) for weevil captures in traps and infested palms detected. High weevil captures or removal of too many infested palms indicates that the strategy is not doing well and needs adjustments.

Systematic geographic information system (GIS)-linked data collection is indispensable, e.g., by using a large number of mapped (traps and weevil catches), the temporal as well as geographical changes in pest distribution can be monitored and infested palms detected by various means can be localized [41]. The future prospect for data collection, compiling and analysing in area-wide RPW-IPM programmes would be to develop and validate mobile apps for smartphones to record geo-referenced data at the field location on a standard form. Recently, FAO has initiated the process to validate the SusaHamra app to assist farmers in better monitoring and

managing the RPW. A global platform is being established for mapping field data and analytics for better decision-making.

At level-2 of the strategy, phytosanitation/quarantine is very important. The main gaps and challenges here are: (i) national/regional phytosanitary/quarantine regulations against RPW are not adequately implemented; (ii) treatment protocols to treat palms prior to transportation and also after arrival at destination are not consistent; (iii) implementation of the regulations is weak due to insufficient staff that is often not trained; and (iv) certified planting material is difficult to get [2, 37]. Recently, Chouibani [11] has addressed these concerns in the FAO guidelines on RPW management. Although chemical protocols available for quarantine purposes are available for date palm offshoots, the need to develop an effective treatment protocol to treat and sanitize large palms for ornamental gardening before transportation has to be addressed on priority. It is the responsibility of respective NPPOs to ensure implementation of the phytosanitary measures against RPW.

The lack of biological control agents against RPW that are field worthy is another major concern. Although there are known biological control agents for RPW, delivery to the target site inside the palm and sustainability of these agents needs to be addressed. Furthermore, the importance of adopting the best agro-techniques related to palm density, frond and offshoot removal and irrigation practices is underestimated. There is scope to conduct research on these aspects to quantify the relationship between these factors and the incidence and severity of RPW. Host plant resistance against RPW is also not very well understood and offers a whole new area of exploration where the traditional plant breeding techniques coupled with advanced molecular based breeding techniques could be used to induce resistance against RPW in the popular palm cultivars. The entire genome of the date palm cultivar 'Khalas' has been sequenced [108, 109]. This could facilitate the integration of genetic engineering techniques into date palm breeding programmes that provide mechanisms to overcome the current constraints to conventional breeding in date palm and help incorporate desirable traits of yield, quality and resistance to abiotic and biotic stresses in date palm [110].

In several countries, the RPW-IPM programme is implemented largely by the state where farmers' participation is minimum or none. This impedes the performance and success of the strategy. Mechanisms need to be devised to increase farmers' participation in RPW-IPM programmes. In this context, Abdedaïem et al., [106] emphasized the need to take up socio-economic studies for enhancing farmers' involvement in the RPW control programme.

During the last few years, there are several publications that have generated data on the cutting-edge molecular aspects of RPW involving RNAi, gene expression, etc. [111–114]. Results of these studies need to be exploited in a way that the control strategy stands to benefit from such basic research.

Faleiro et al. [2] report that in recent years, a large number of new RPW-IPM tools (detectors, surveillance drones, pesticides, palm injectors, semiochemicals, biological control agents, palm shredders, microwave treatment devices, etc.) are available in the market. These IPM tools need proper testing and validation at the national and regional levels so that only field worthy technologies that are not costly and easy to use are made available to the farmers.

7. Conclusions

The red palm weevil remains to be the invasive key pest threatening palms survival around the world. International trading and transportation of infested planting material (palms) for plantations and landscape purposes are the main

introduction pathways into new non-invaded areas. Current management strategies against RPW depend on monitoring and mass trapping using pheromones, agronomic and phytosanitary measures and to some extent biological control. Capacity building and quarantine measures are also among the RPW-IPM components. Despite major global efforts to combat the weevil, many gaps and challenges, in management strategies, need to be addressed. Such challenges include early detection of infestation, optimization of pheromone-baited traps, removal of highly infested palms, overdependence on the use of insecticides and participation of farmers in the control efforts. Future prospects of RPW management may include validation of management programmes, testing of high-tech technologies for practical field application and the use of RNAi technology in management programmes. It can be concluded that managing RPW in the field is not an easy task but with adequate resources, appropriate interventions supported by good coordination, planning and financial resources, the pest can be effectively controlled with the current technologies.

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